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1. Your reference

   1909201/AM

2. Patent Application Number

   0404585.2 — 1 MAR 2004

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

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   Harston Mill
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   Patents ADP number *(if known)* 7970296002

   If the applicant is a corporate body, give the country/state of its incorporation — Country: **England** State:

4. Title of the invention

   2D POSITIONING SENSOR

5. Name of agent "Address for Service" in the United Kingdom to which all correspondence should be sent

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   Patents ADP number 1826001

6. Priority: Complete this section if you are declaring priority from one or more earlier patent applications filed in the last 12 months.

Country	Priority application number	Date of filing

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Priority documents	
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Statement of inventorship and right to grant of a patent *(Patents form 7/77)*	**1 + 1 copy**
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11. I/We request the grant of a patent on the basis of this application

Signature Beresford & Co
BERESFORD & Co

Date 1 March 2004

12. Name and daytime telephone number of person to contact in the United Kingdom

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Tel: 020 7831 2290

INITIAL PATENT FILING

Subject: 2D positioning sensor
Date: 27/02/04
Inventors: Victor Zhitomirskiy

1 INTRODUCTION

In this patent application we describe a novel measurement system in which the precise positioning of the hidden object can be achieved remotely even through the thick metallic walls of an enclosure. The approach described below enables large-scale low-cost positioning system with sub-millimetre resolution (electronic calliper) for in-plane motion and sub-degree resolution for angle rotation measurements.

The system is based on detecting a magnetic field from a permanent magnet attached to the hidden object. This magnetic field will penetrate through most non-magnetic materials including thick plates of metal. Thus a suggested positioning system would be able to operate in the environment typical for an automotive or production line industry. We will discuss how a soft magnetic foil could be used to detect the "magnetic null" node of the in-plane magnetic field originated from the permanent magnet. We will discuss the cheap measurement set-up based on the simple PCB design, which is able to provide an absolute position of the permanent magnet with extremely high accuracy.

The main inventive step of the patent is introduced by a new concept for a large-scale magnetic position sensor based on using a large-area soft magnetic film. A proposed system consists of two separate parts: the magnetic film (most probably a permalloy foil or an amorphous soft magnetic alloy foil) and a special pattern created on a PCB-like board. The signal measurement is enabled by cheap electronics preferably mounted on the same PCB board.

2 PRIOR ART

2.1 Inductive position sensors

A positioning technology based on inductive coupling has previously been applied enabling a diverse range of measurement solutions.

The principle of inductive sensor is based on inductively out-coupling of a field in the movable element that, in turn, inductively feeds back to the receiving conductor loops, which have a special geometry. The geometry of the receiving conductor loops is chosen such that the induced voltage in the receiving conductor loops depends upon the position of the movable element.

In some more specific resonant embodiments the inductive coupling systems will consist of two relatively moving parts. Typically, one part carries an excitation winding and two or more sensor windings while the other part carries a resonant circuit. The magnetic coupling between the resonant circuit and each of the sensor windings varies with position so that, by applying an oscillating signal at the resonant frequency of the resonant circuit to the excitation winding, a signal is induced in each of the sensor windings, which oscillates at the resonant frequency but whose amplitude varies as a function of the relative position of the two parts of the measurement system.

Numerous examples of inductive positioning systems for non-contact linear and rotary position encoders are available in the recent patents from companies like Mitutoyo Corporation (US6646433, US2001/0024123, US6335618, US6329813, US6002250, US5886519), Hella KG Hueck (US6483295, US6384598, US 6236199), Generics Group (WO 03/038379, WO 02/097374, WO 01/42865, US6534970, US6522128, US6489899, US6304014, US6249234, US6124708, US5815091), and Cherry GmbH (US6593730).

The main limitation of the inductive position technique comes from the effect of shielding the AC electromagnetic field by conductive plates. As a result, the technique of inductive sensing will work only when the space between two movable members is free from metallic walls. More precisely, a very thin non-magnetic metallic plate will allow measurements, but at very low frequency.

The skin effect in the conducting materials is caused by the fact that the process of the penetration of the magnetic field inside the conductor is similar to the diffusion process. In the case of a DC magnetic field this is not important because after some delay the magnetic field penetrates through the thick conductor. But this situation is different for an AC magnetic field. The amplitude of an AC magnetic field falls below the surface of the conductor as $B \sim \exp(-x/l)$, where l is the skin depth. The value of the skin depth is given by the formula

$$l \sim \frac{c}{\sqrt{8\pi\mu\sigma\nu}}$$

where μ is the permeability of the material, σ is the electric conductivity and ν is the frequency. The typical skin depth for the copper is about 0.5mm at $\nu \sim 10kHz$. For other materials like aluminium and stainless steel the skin depth is larger because of poorer conductivity. However, for magnetic steels with a significantly large permeability μ the skin depth is greatly reduced as it follows from the formula.

2.2 Magnetic field position sensors

The usage of a permanent magnet attached to the object of interest for sensing purposes is normal practise in the automotive or robotic industry, in which metallic parts typically surround a moving object. Usually a magnetic sensor located at the fixed point detects the magnetic field from the moving permanent magnet. In some particular embodiments a fringing magnetic field of the fixed permanent magnet is affected by the tooth-like structure of the moving ferrous object thus producing a periodic signal at magnetic sensor. Systems of this type are described in the recent patents from such companies as Robert Bosch (US6622388, US6433535, US6212783, US6163746), BVR Aero Precision Corp. (US6326781), Kabushki Kaisha Tokai Reika Denki Seisakusho (US6271663), US Philips Corporation (US6064197), Denso Corporation (US6448762), and Volvo Construction Equipment (US5918199).

The main limitation of this approach for detecting magnetic field from the magnet is a fast reduction of the value of the magnetic field with a distance from the magnet. At large distances $H \sim 1/x^3$ and a typical distance between a magnet and a magnetic sensor should not exceed few centimetres.

A magnetised scale with a periodic magnetic field pattern could enable a robust means of measuring large-scale displacement of the magnetic reading head. The main advantage of a periodic magnetic scale is an increased range of displacement measurements. Devices based on this principle are described in the patents US6629371 (Pentax Corporation), US6332278 (Brown&Sharpe TESA SA), US6118271 (Scientific Generics), and US5461311 (Kabaya Kogyo Kabushiki Kaisha).

A large-scale distributed magnetic sensor might enable another approach of increasing the range of displacement measurements. Some attempts of enabling large-scale magnetic sensors are described in the patents from companies such as Delphi Technologies (US6486659, US6326782), Koninklijke Philips Electronics (US6690157). However the approach described in these patents includes an arrangement of an array of magnetic field sensors and so fails to suggest a cheap and economic way of constructing a really large-scale positioning encoder.

2.3 Magnetic film as a point magnetic sensor

The typical magnetic sensor can be either semiconductor film device (like a Hall sensor or a magnetoresistor) or a device based on magnetic films. Devices based on magnetic films are sensitive to the magnetisation of soft ferromagnetic films. There are different ways of using magnetic films. Roughly magnetic film sensors might be split into four main groups:

- Anisotropic magnetoresistance (AMR)

  In a permolloy film (Ni_xFe_{1-x} or Ni_xCo_{1-x}) electric resistance if measured alone the magnetic moment or perpendicular to the magnetic moment can differ by a few percent due to an anisotropy in the scattering of s-electrons on d-electrons. The most common material is $Ni_{0.8}Fe_{0.2}$ with zero magnetostriction. It has magnetoresistance of the order of 2%, which is saturated around 20. Oe. As a result, sensitivity 1/R*dR/dB in this magnetic field region is around 10 (1/T). In practise a hard ferromagnetic layer adjacent to the permolloy film is used to align magnetic moment in the permolloy film perpendicular to the direction of an in-plane magnetic field to be sensed. External in-plane magnetic field causes rotation of magnetic moment in plane of the film in respect to the applied current.

- Giant Magnetoresistance (GMR)

  Alignment of a magnetic moment in the ferromagnetic multilayer structures or granular systems causes a drop in the resistance due to the spin-dependent scattering. There are plenty of different geometries and materials used to produce such magnetoresistors. Examples can include polycrystalline film of $La_{1-x}MnO_3$ with sensitivity of the order of 8 (1/T) at magnetic fields below 100 Oe; CoCu/Cu multilayer system with a sensitivity of 10 (1/T) at magnetic fields below 100 Oe. The frequency response of such systems is limited by the frequencies of the order of 1GHz.

- Giant Magneto Impedance Effect (GMI):

  The Giant Magneto Impedance Effect (GMI), which shows as the huge variation of the electrical impedance as a function of the applied magnetic field, is based on the magnetic field dependence of the skin depth. In the GMI material the skin depth defines the depth of the penetration of the alternating current into the ferromagnetic wire or ferromagnetic film. The resistance of the wire or the film towards the AC electric current varies accordingly.

  This effect can be found in the range of high frequency over 1 MHz for an excitation current in an amorphous ferromagnetic wires made from material like FeCoSiB, FeCoCrSiB or CoSiB. GMI has the highest sensitivity at exceptionally small magnetic fields. The sensitivity reaches 10 000 (1/T) at magnetic fields below two Oe. In a thin film device a

significantly smaller sensitivity of 500 (1/T) was achieved in a slightly larger window of magnetic fields below 20 Oe. Main disadvantages: frequency of an external magnetic field to be sensed should be below 1MHz; small amplitude of external magnetic field can destroy a sensitivity of the GMI sensor due to the saturation of the magnetic field response.

- Flux gate sensor

  The most common type, called the second harmonic device, incorporates two coils, a primary and a secondary, wrapped around a common high-permeability ferromagnetic core. The core's magnetic induction changes in the presence of an external magnetic field. A drive signal applied to the primary winding at frequency *f* (e.g., 10 kHz) causes the core to oscillate between the saturation points. The secondary winding outputs a signal that is coupled through the core from the primary winding. This signal is affected by changes in the core's permeability and appears as an amplitude variation in the sensing coil's output. The signal can be demodulated with a phase-sensitive detector and low pass filtered to retrieve the magnetic field value. Another way of looking at the flux gate operating principle is to sense the ease of or resistance to core saturation caused by the change in its magnetic flux. The difference is due to the external magnetic field. A well-designed flux gate magnetometer can sense a signal in the tens of microgauss range, as well as measure both magnitude and direction of static magnetic fields. The upper frequency band limit is ~1 kHz due to the drive frequency limit of ~10 kHz. These devices tend to be bulky and not as rugged as smaller, more integrated sensor technologies.

3 FERROMAGNETIC FILM AS A LARGE SCALE SENSOR

The main idea of using a soft ferromagnetic field as a detector of the location of the permanent magnet is shown in Fig.1. The permanent magnet produces a strong fringe magnetic field. The magnetic field is directed from the North pole of the permanent magnet to the South pole and all magnetic field lines are closed (see Fig.1).

The component of the magnetic field directed perpendicular to the soft ferromagnetic film is not able to change the magnetisation of the film because of the form of the boundary condition for the normal component of the magnetic induction B:

$$B_{2,n} = B_{1,n} = H_{1,n}$$

The boundary condition for the tangential component of the magnetic field H is given by :

$$H_{1,t} = H_{2,t}$$

And so inside the film :

$$B_{2,t} = H_{1,t} + 4\pi M$$

where M is a magnetisation vector of the ferromagnetic film directed in the plane of the film. The vector M is restricted in the amplitude by the value

$$M = nM_0$$

where M_0 is a magnetic moment of a molecule and n is a mean number of the molecules in the unit volume. In a soft ferromagnetic film a typical value of the magnetic field $H_{1,t}$, which is enough to saturate the magnetisation vector M is about few Oe. The permeability μ, which enters the formula for a skin depth is given by :

$$\mu = \frac{\partial B}{\partial H} = 1 + 4\pi \frac{\partial M}{\partial H}$$

The permeability μ is a non-monotonic function of the in-plane component of the magnetic field H. It reaches the maximum value of the order of a few thousands in magnetic fields below a few Oe. The strong magnetic field dependence of the permeability μ causes the strong magnetic field dependence of the skin depth and strong variation of the imaginary part of the eddy currents induced in the metallic layer by an external AC electromagnetic field.

For our 2D magnetic positioning system we propose to use inductive coupling to sense the region with the high value of the permeability μ created by the "magnetic null" of the in-plane magnetic field.

4 MEASUREMENT SET-UP: IN-PLANE POSITIONING

4.1 Inductive coupling

The spot of the "magnetic null" of DC magnetic field from the permanent magnet will cause a spot on the ferromagnetic film in which permeability is significantly different from outside the spot. Moreover ,the permeability inside the spot will be a strong function of the position inside the spot as shown in Fig.1. This artificial inhomogeneity in the ferromagnetic film, which moves together with the permanent magnet, might be used to enable a large-scale displacement encoder.

The inductive eddy current technique was successfully applied to locate different defects in the metallic plates including microscopic cracks and some surface impurities. These defects were measured due to the fact that they introduce an inhomogeneous response to the AC electromagnetic field.

Some versions of inductive position sensors were based on moving conducting targets, which introduced an inhomogeniety in the space around balanced coils of the receiver. One example of such a measurement set-up is described in the patent US4820961 from Kollmorgen Corporation.

The inhomogeniety in the soft ferromagnetic film will also induce a response in the closely located balanced coils. The phase and the amplitude of this induced signal will depend upon location of the "magnetic null" spot from the moving permanent magnets, and will also be defined by the details of the geometry of the balanced coils. The inductive coupling set-up will represent the most straightforward and cheapest way of constructing an electronic output for an encoder based on a soft ferromagnetic film and a permanent magnet.

4.2 Matrix approach

Let's consider an array of inductors shown in Fig.2. An inductive coupling between the horizontal and the vertical stripes can be minimised by using correct geometry. An AC magnetic field generated by the stripe is shown in the caption to Fig.2. It is positive in the region enclosed by the windings and is negative outside of this region because all magnetic lines are enclosed. That is why a positive mutual inductance originates from the region where the vertical and the horizontal stripe overlap and the negative mutual inductance is produced in the area outside this region. An AC magnetic field decreases as $H \sim 1/R^3$ so it is possible to cancel the mutual inductance between the vertical and the horizontal stripes by adjusting by how much they overlap. Thus, a set of balanced coils can be produced. In such cases the AC voltage induced in the vertical stripe due to the AC current flowing in the horizontal stripe is reduced to zero (see Fig.2).

The presence of the saturated soft ferromagnetic film will not influence the mutual inductive coupling between stripes. But in the region of the "magnetic null" (see

Fig.1) where the external field from the permanent magnet does not saturate the soft ferromagnetic film, the property of the soft ferromagnetic film will become strongly inhomogeneous. Typical values for the permeability μ of the amorphous ferromagnetic field exceeds a few thousand for frequencies around 1MHz. The permeability μ for saturated regions of ferromagnetic film is close to unity. That is why the high contrast ratios for the skin depth in the "magnetic null" spot and outside of this spot can be automatically achieved. As a result the cross inductance, and hence, an induced voltage in the configuration shown in the Fig.2 will strongly depend on the presence of the "magnetic null" region in the vicinity of the area where the vertical stripe overlaps with the horizontal stripe. The induced voltage will depend on the distance between the "magnetic null" spot and the centre of the pixel in the array in the manner shown in the caption to the Fig.2. The characteristic length in this dependence is determined by the geometrical size of the stripe rather than on the diameter of the "magnetic null" spot. The value of the induced voltage, on the other hand, will strongly depend on the size of the "magnetic null" spot as it produces a perturbation in the AC magnetic field generated by the drive stripe coil. Nevertheless, by comparing a signal on adjacent pixels of the matrix shown in Fig.2 an exact position of the "magnetic null" spot can be calculated with high accuracy.

The exact position of the "magnetic null" region where the external field from the permanent magnet does not saturate the soft ferromagnetic film is very sensitive to the angle between the permanent magnet and the soft ferromagnetic film. We will discuss this behaviour in more details in the section devoted to the angular positioning. Here we want to emphasise that this dependence will produce a potential problem to determine unambiguously the position of the permanent magnet even if the position of the "magnetic null" is extracted. To solve this problem we have to restrict an application area of this measurement set-up to the case where the angle between the magnet and the plane of the ferromagnetic film is fixed. This means that ideally the magnet can't be rotated during 2D position measurements. This is a very serious restriction for this positioning technology.

4.3 Phase approach

It is necessary to make N^2 measurements to obtain information about the mutual inductance in the matrix shown in Fig.2. Another approach, which is closer to one used for a typical inductive position encoder, could be used to significantly reduce the number of measurements which should be done to find the position of the region of the "magnetic null" in the plane of the soft ferromagnetic film.

The major concern with a set-up such as the one described below will come from the potential sensitivity of the induced signal to the slow variation of the permeability of the soft ferromagnetic film in the region far away from the "magnetic null" spot of the permanent magnet.

This problem was tested experimentally and it was found that the rate of the change of permeability is most important parameter, which determines amplitude of the pick-up signal. For instance, once the distance between the permanent magnet and the film was increased above few centimetres, hardly any signal was induced by the "magnetic null" spot in the set of balanced coils. The inhomogeneity in the eddy currents created by the variation in the permeability is not straightforward. A large permeability will mainly alter phase rather than amplitude of the eddy currents. So only the rapid change of the permeability along the pitch of the inductive coupler will be enough to induce the large amplitude in the otherwise balanced coil set.

Thus, the embodiment described below do not rely on an assumption that the permanent magnet will be able to saturate the whole ferromagnetic film outside of the "magnetic null" region. We just assume that the "magnetic null" from the permanent magnet correspond to the only area in the ferromagnetic film where rapid change of the permeability occurs on a small scale.

In Fig.3a we show an example of the coil arrangement in which the flux produced by the drive coil in the main frame coil is zero due to the geometry of the drive coil. As we discussed before, the "magnetic null" spot can disturb the AC magnetic field produced by the drive coil and so is able to induce a signal in the main frame coil. This signal will oscillate around zero (see Fig.3a) with a period determined by the geometrical period of the drive coil. The amplitude of the signal will depend on the "magnetic null" size. If two coils with exactly the same period are shifted by a quarter of the period, a "sine" and "cosine" signal will be measured if drive coils are exited one after another. As a result an exact phase of the "magnetic null" spot in respect to the fixed drive coils frame might be calculated as $\arctan(V_1 / V_2)$.

The next step in providing an encoder based on this principle is to obtain the same phase measurement for another couple of the "sine" and "cosine" coils having slightly different periods. An example of such an approach is two sets of "sine" and "cosine" coils with the total number of periods different by just one (see Fig. 3b). In this case we can obtain a ""magnetic null" position unambiguously by knowing the absolute phase of the spot in these two frames.

Furthermore, an exact position in both X and Y directions can be determined by using a perpendicular set of drive coils as shown in Fig.3c. Now the whole positioning will take just eight consecutive measurements. The measurement set-up of such encoder can easily achieve a space resolution of better than a 1/100 of the drive coil period.

As inductive set-up shown in Fig.3 doesn't rely on resonant measurements, so all eight measurements could be performed simultaneously at eight different frequencies thus providing continuous immediate readings for the position of the permanent magnet in X-Y directions.

5 MEASUREMENT SET-UP: ANGLE POSITIONING

5.1 Magnet attached out of axis – intelligent bearing

As we mentioned above the rotation of the magnet could produce significant problems for the encoder based on soft ferromagnetic film. However in a specific case when the movement of the magnet is restricted to the rotation only one axis, the simple measurement set-up will help to position the angle of rotation extremely accurately.

An example of such a system, which might be a part of an integrated intelligent bearing, is shown in Fig.4. As it obvious from Fig. 4, this case is very similar to the linear motion encoding and so could be based on the approach for inductive coupling described previously (see Fig.3b).

5.2 Magnet hidden inside shaft

In Fig.5 we show the design of the system where the permanent magnet is attached perpendicular to the axis of rotation. In Fig.5a the soft ferromagnetic film forms a cylinder with the axis roughly coinciding with the axis of rotation. The two nodes of the "magnetic null" region will be formed by both the North and the South poles of the permanent magnet. The magnetic field in the plane of the ferromagnetic film is given by a simple formula $H_{II} = \sin(\alpha)$ as shown in Graph A in Fig.5. The film is completely saturated by the magnetic field from the permanent magnet except the two "magnetic null" regions. Even a significantly strong external magnetic field is not able to destroy this arrangement. It can only shift the position of the node by the distance $\Delta x \sim H_{ext} / \frac{\partial H}{\partial x}$. Due to the large value of the derivative $\frac{\partial H}{\partial x}$ this displacement would be relatively small. In addition to the angle of the axis the set-up shown in Fig. 5a can measure the vertical position of the magnet. So an angular rotation and the vertical displacement of the axis of the rotation can be sensed simultaneously. We can use a simple approach based on the phase measurement technique described in the previous chapter (see Fig. 3c) to detect the position of the "magnetic null". The only drawback of the set-up shown in Fig. 5a is an uncertainty in the angle caused by the fact, that with the proposed technique it is impossible to detect the sign of the magnetic field, instead only the "magnetic null" spot is detected. That is why the period of the detected signal is equal to π rather than to 2π.

The soft ferromagnetic film can also be placed in the plane perpendicular to the plane of the shaft as shown in Fig. 5b. The magnetic field amplitude in the plane of the film along the radius of the sensor is shown in Graph B-2 of Fig. 5. Graph

B-1 in Fig. 5 shows the magnetic field in the plane of the film along the diameter of the measurement set-up.

A permanent magnet could be fixed at the angle to the direction perpendicular to the axis (see Fig. 6). In such cases a signal on the sensor will have a period equal to 2π rather than to π as in the case described previously (compare with Fig. 5b). The magnetic field amplitude in the plane of the film along the radius of the sensor is shown in Graph 1 of Fig. 6. Graph 3 of Fig. 6 shows the magnetic field in the plane of the film along the diameter of the measurement set-up. Graph 2 of Fig. 8 shows the dependence of the radial position of the first and the second node of the "magnetic null" as a function of the angle between the permanent magnet and the axis. The radial position of the spot is equal to $1/\sqrt{2}h$ if the permanent magnet is fixed perpendicular to the axis. The radial position of the first spot is almost linearly reduced with the angle between the permanent magnet and the axis (see Graph 2 of Fig. 6). The radial position of the second spot quickly increases when the same angle is decreased. From Graph 3 of Fig. 6 it is obvious that even 70 degrees is enough to move the second spot far enough away from the measurement set-up so that finally only one spot of the "magnetic null" will be sensed by the inductive detector set-up. For example, it will be possible to use a phase approach to detect the angular position of the "magnetic null" (see Fig. 3a). The measured coordinate along the circumference determines the radial position of the "magnetic null" spot. An accuracy of angle positioning better than 0.5 degrees might be easily achieved.

In Fig. 7 we show another possible configuration. The soft ferromagnetic film is located on the surface of the cone so that the permanent magnet is directed perpendicular to the surface of the film. In this case the radial position of the spot is given by

$$R = h * \tan(\beta)$$

This geometry has an obvious advantage in the case where the radial position should exceed the value $R \sim 0.7h$ (see Graph 2 of the Fig. 6).

In the case where the diameter of the shaft is larger than a few centimetres, another approach might be suggested. The magnet could be mounted perpendicular to the axis but the length of the magnet will be just a fraction of the diameter. As discussed above, the magnet hardly introduces a pick-up signal if moved away by more than three centimetres from the soft ferromagnetic film. Thus, the system shown in Fig. 8a will sense only one "magnetic null" spot generated by the permanent magnet and so ambiguity in the angle measurements will be removed.

For the set-up shown in Fig. 8 the one "magnetic null" spot will always be projected on the measurement set-up during the rotation of the shaft. The second "magnetic null" spot will move out of the measurement set-up closer to the centre of the shaft because of the out-of centre positioning of the permanent magnet.

The measurement set-up shown in Fig. 8a and Fig. 5a allows the simultaneous measurement of rotation and movement of the shaft as a whole along the axis of rotation. Further examples of such set-ups are shown in Figures 9a and 9b. In the case shown in Fig.9b multiple rings of soft ferromagnetic films are used. During the movement of the magnet along the axis of rotation the radial position of the "magnetic null" spot on a particular film changes continuously. There is only a limited range of the height h between the magnet and the plane of the ferromagnetic film, where the "magnetic null" spot will fit radially onto the film. A multiple set of ferromagnetic films might allow to have "magnetic null" spot on one of the films regardless of the movement of the permanent magnet along the axis of rotation. The inductive coupling set-up might be attached to each film separately or located in the gaps between films at equal distances between the films.

5.3 Ball joint geometry

Another example of the angular positioning system where the axis is fixed in a ball joint is shown in Fig.10. A permanent magnet should be attached parallel to the axis to provide a predictable location of the nodes of the "magnetic null" on the soft ferromagnetic film located below the plane where the ball joint is fixed. The inductive coupling set-up should be based preferably on the 2D-phase approach described previously (see Fig. 3c). The area of the main frame coil should be small enough so that the second node of the "magnetic null" region will not contribute to the signal on the detector. This condition is easy to fulfil if a gap between the plane of the soft ferromagnetic film and the ball joint is introduced. In the caption to Fig.10 we show the dependence of the radial position of the nodes of the "magnetic null" against the angle θ between the axis and the plane of the film. Two curves are shown. The first one corresponds to the zero gap between the soft ferromagnetic film and the ball joint. The second one corresponds to the gap, which is equal to half of the length between the magnet and the ball joint. The latter case is most interesting because it significantly reduces the possibility for overlapping between two nodes of the "magnetic null".

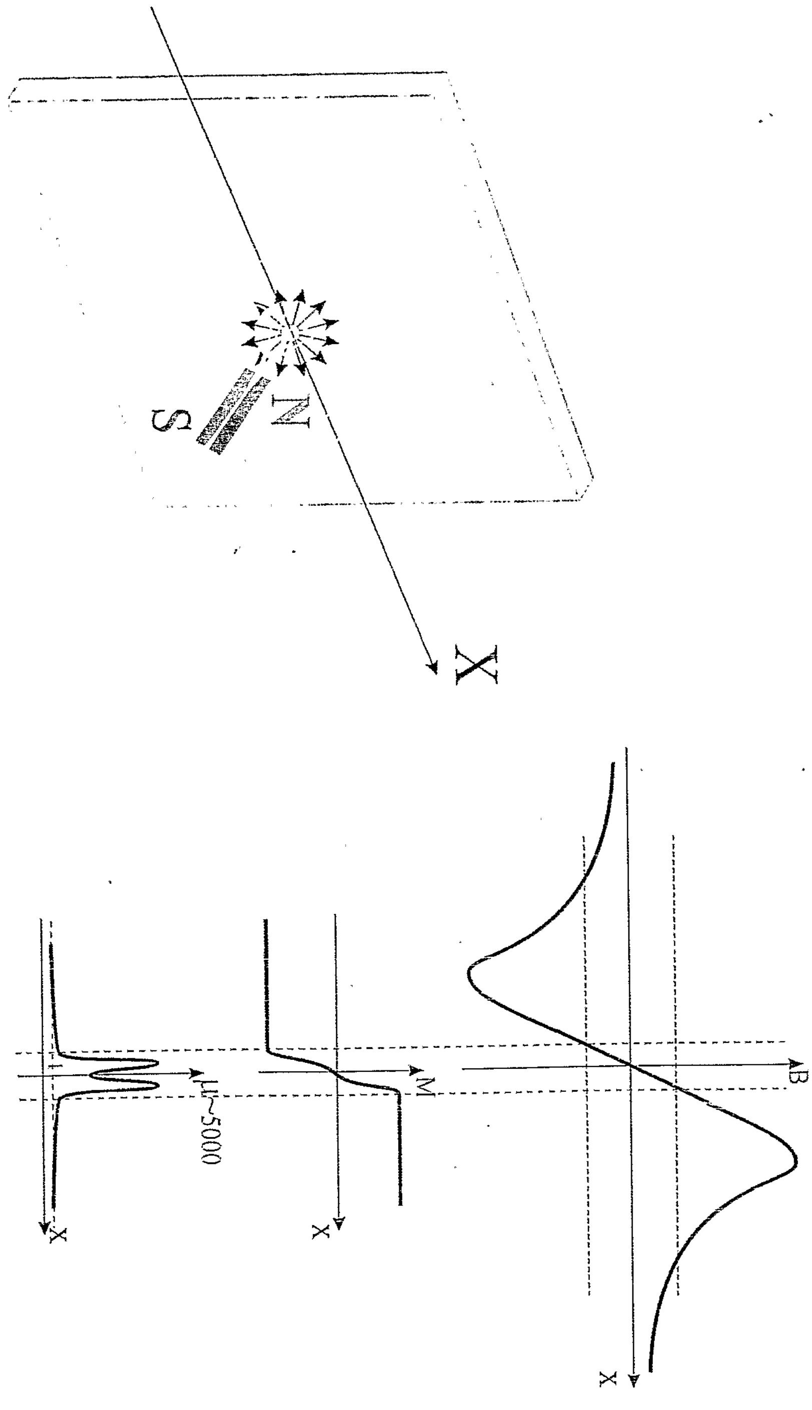


Fig 1

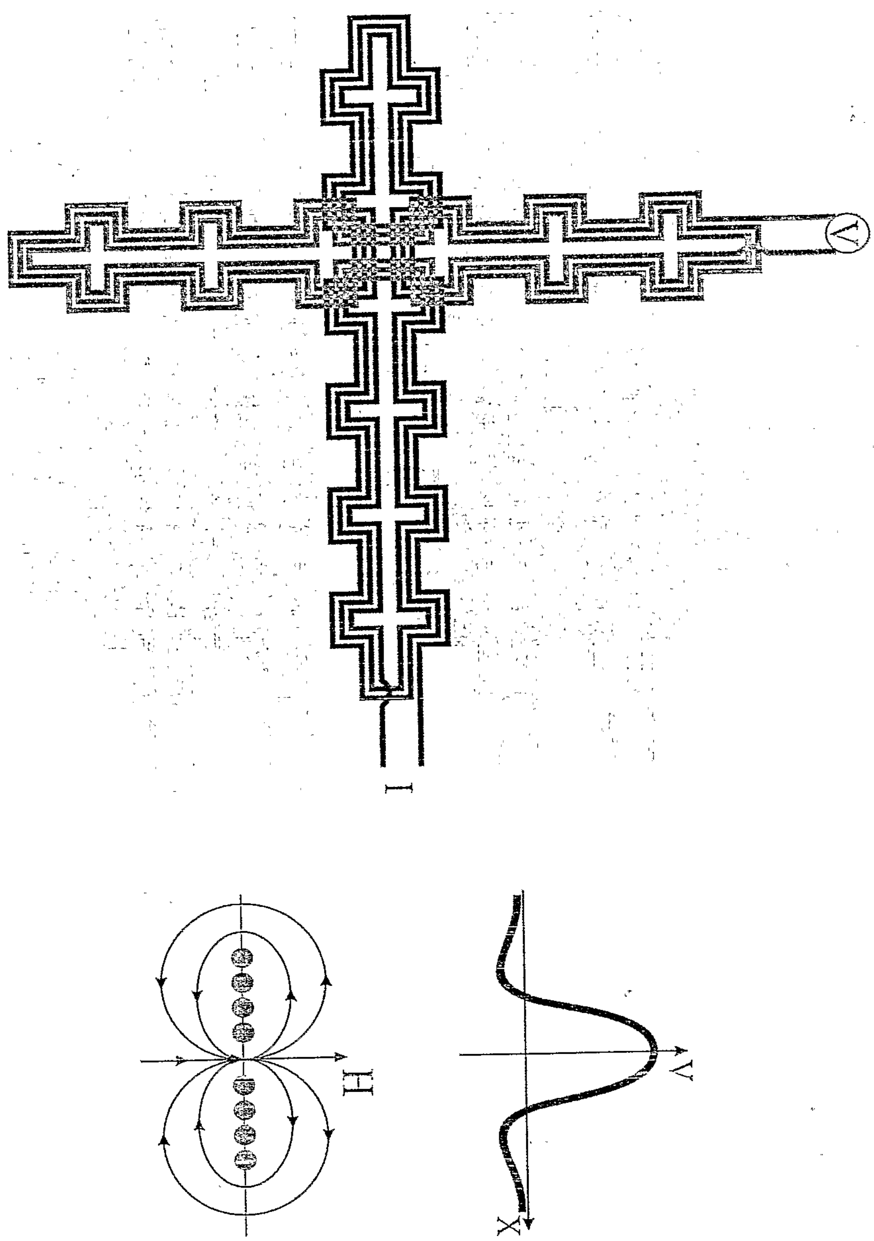


Fig 2

Fig 3

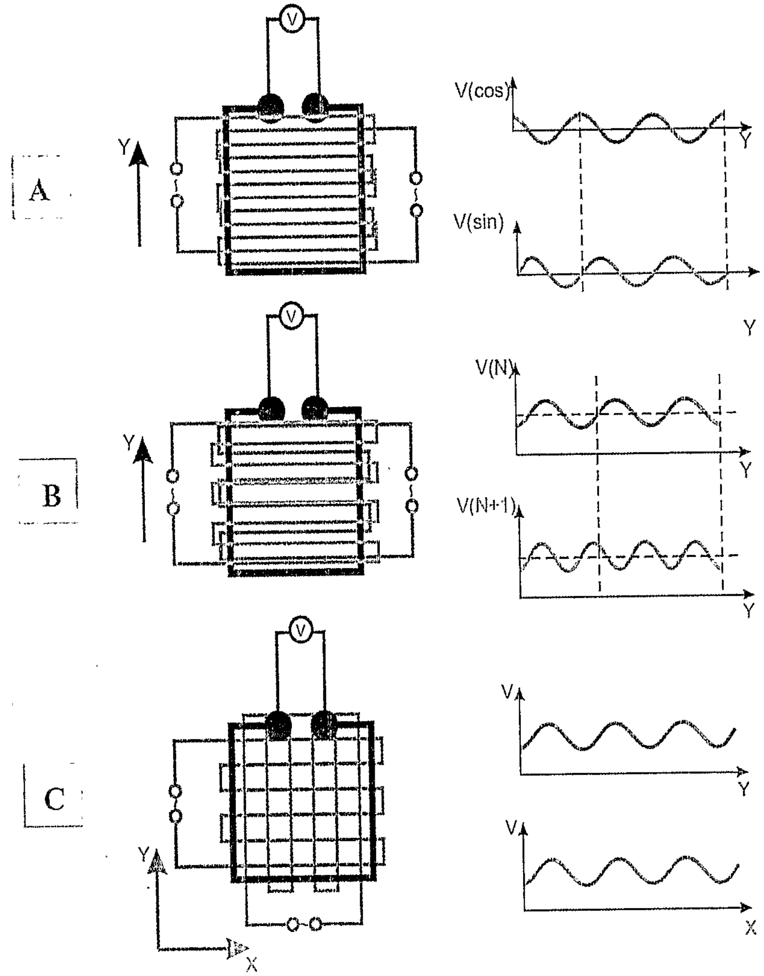


Fig 4

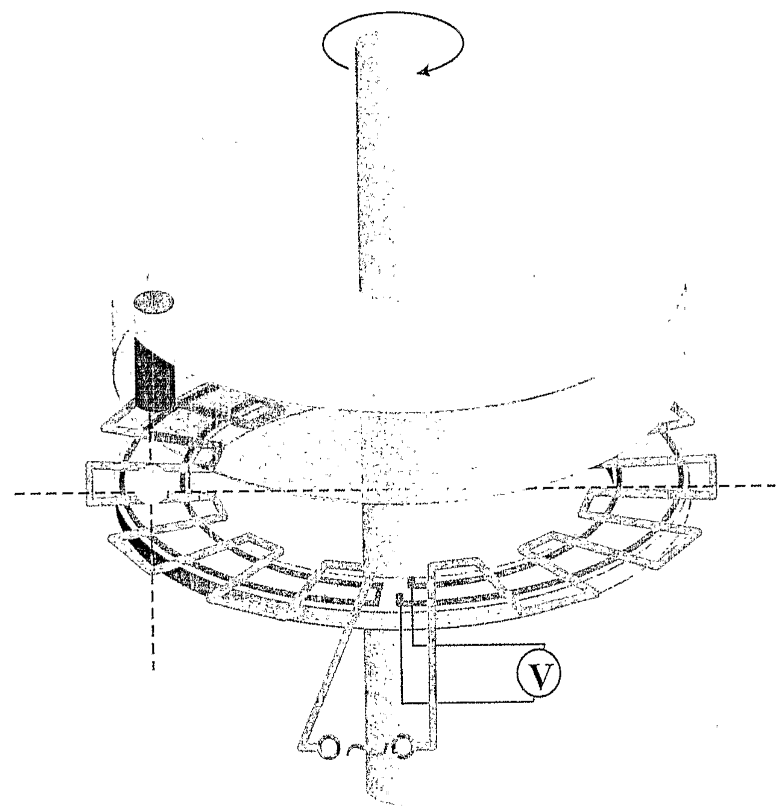
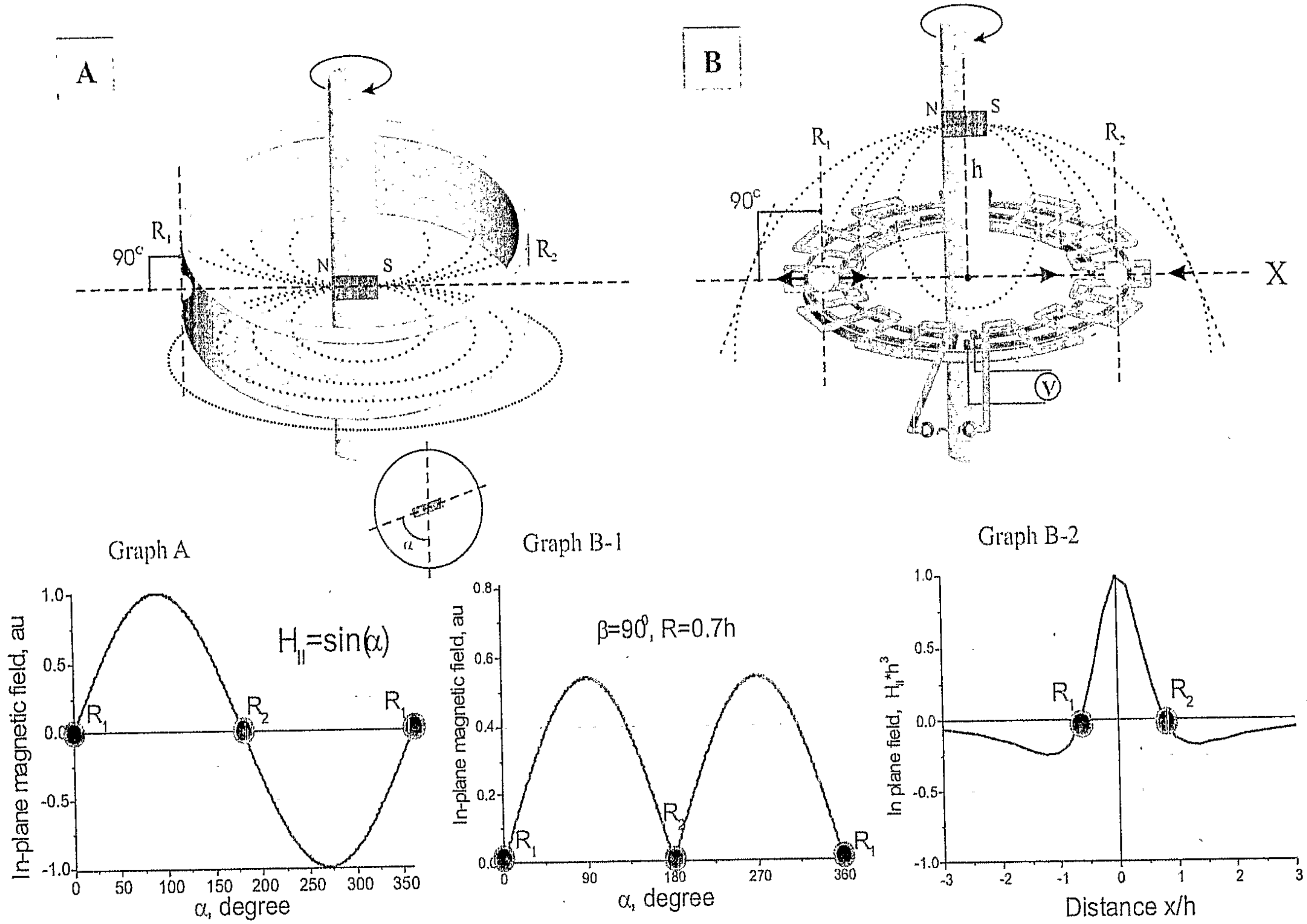


Fig 5



A
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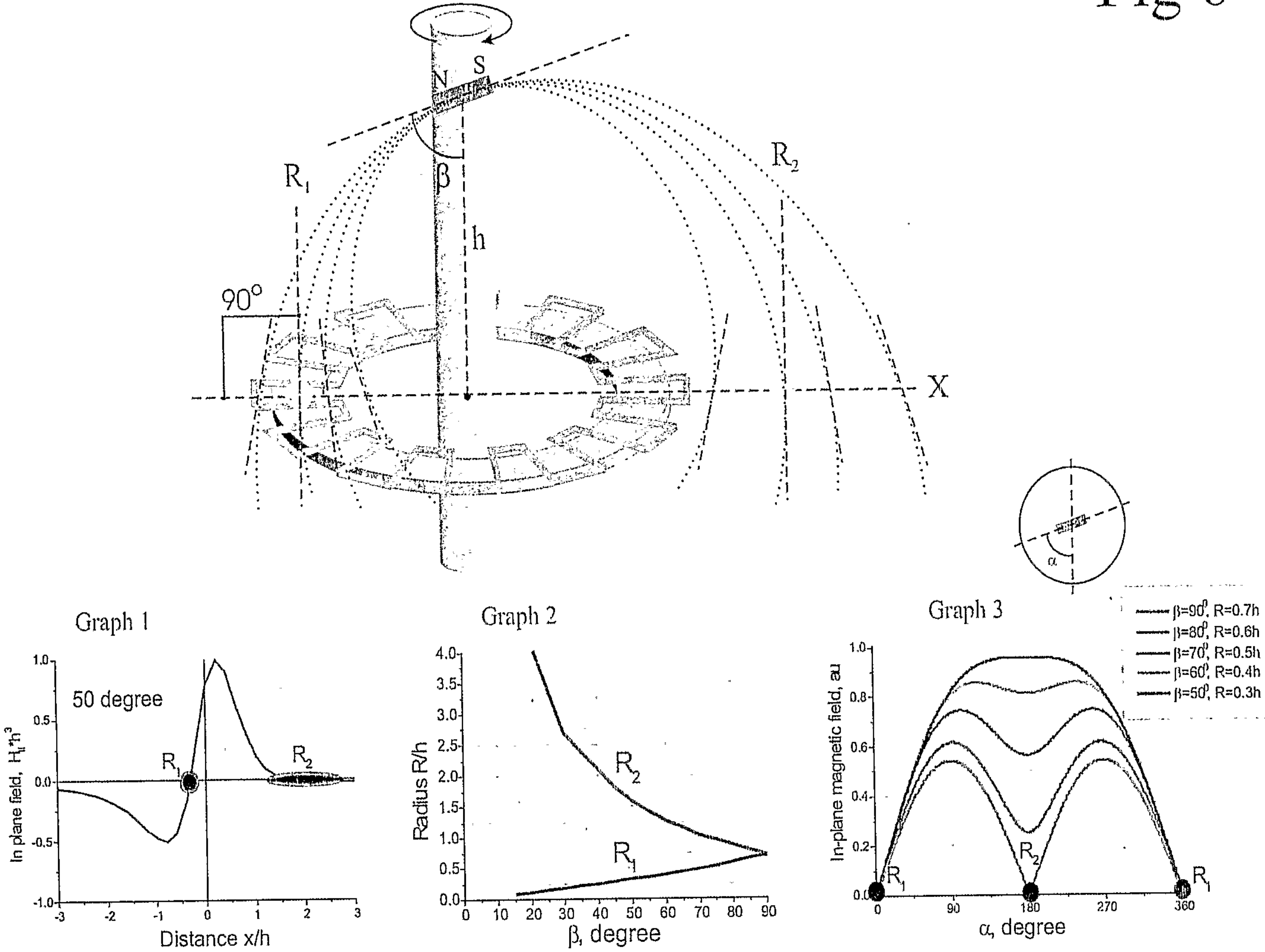
X
V
Graph A
Graph B-1
Graph B-2
$H_{||}=\sin(\alpha)$
$\beta=90^0$, R=0.7h
In-plane magnetic field, au
α, degree
In plane field, $H_{||}*h^3$
Distance x/h

Fig 6



N
S
β
h
R1
R2
90°
X
α
Graph 1
50 degree
In plane field, H*h^3
Distance x/h
Graph 2
Radius R/h
β, degree
Graph 3
In-plane magnetic field, au
α, degree
β=90°, R=0.7h
β=80°, R=0.6h
β=70°, R=0.5h
β=60°, R=0.4h
β=50°, R=0.3h

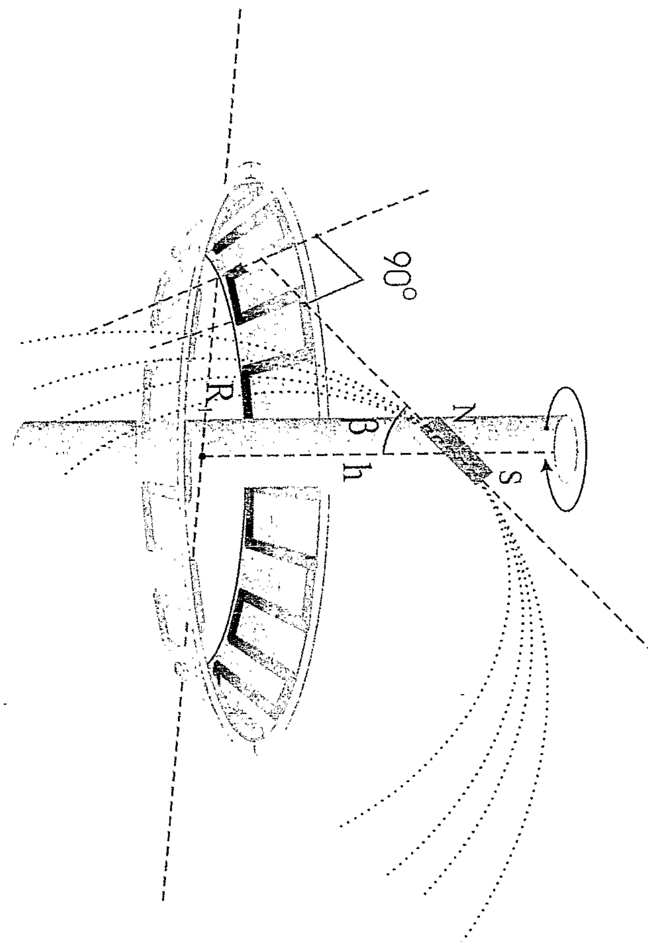


Fig 7

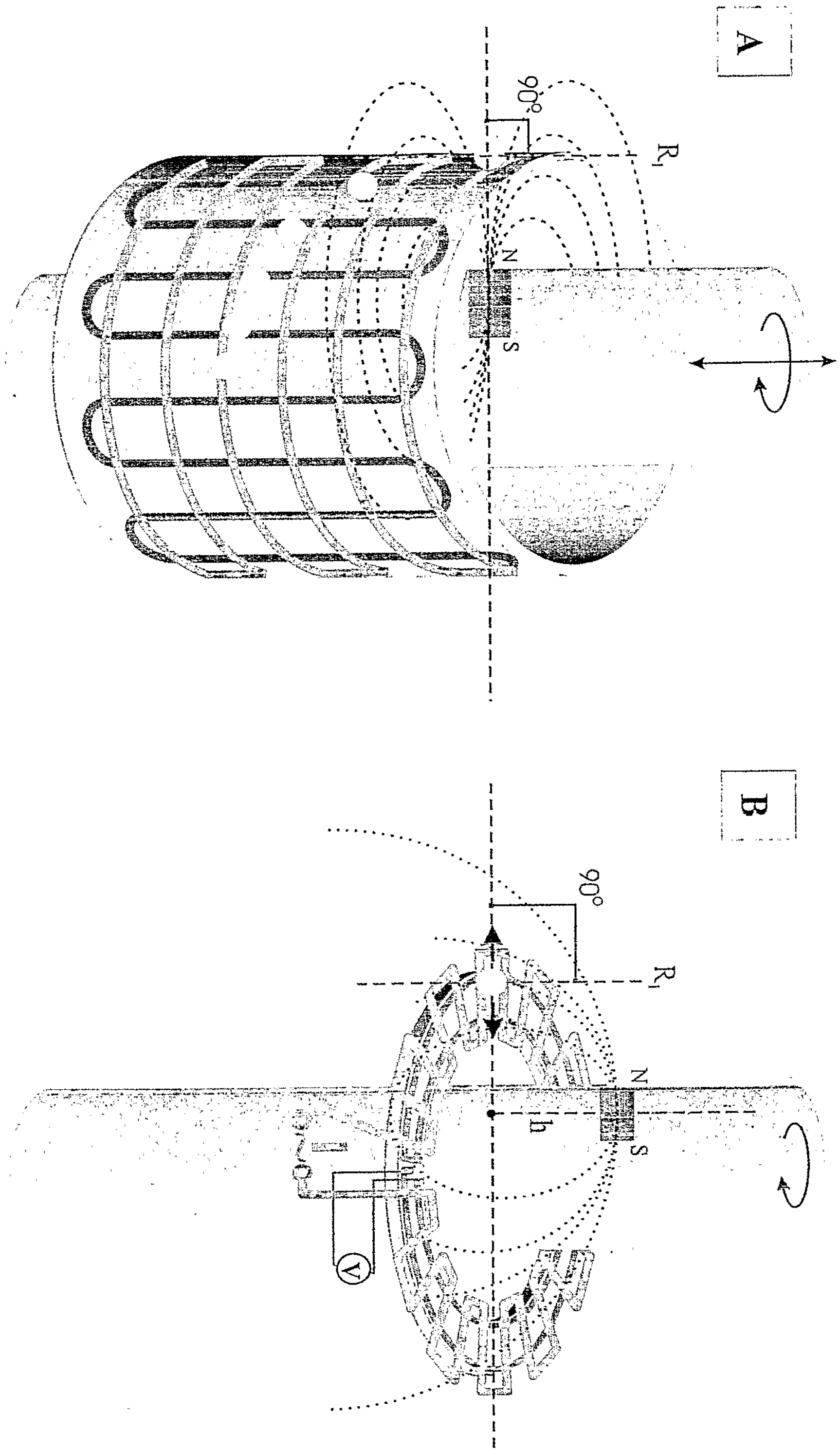


Fig 8

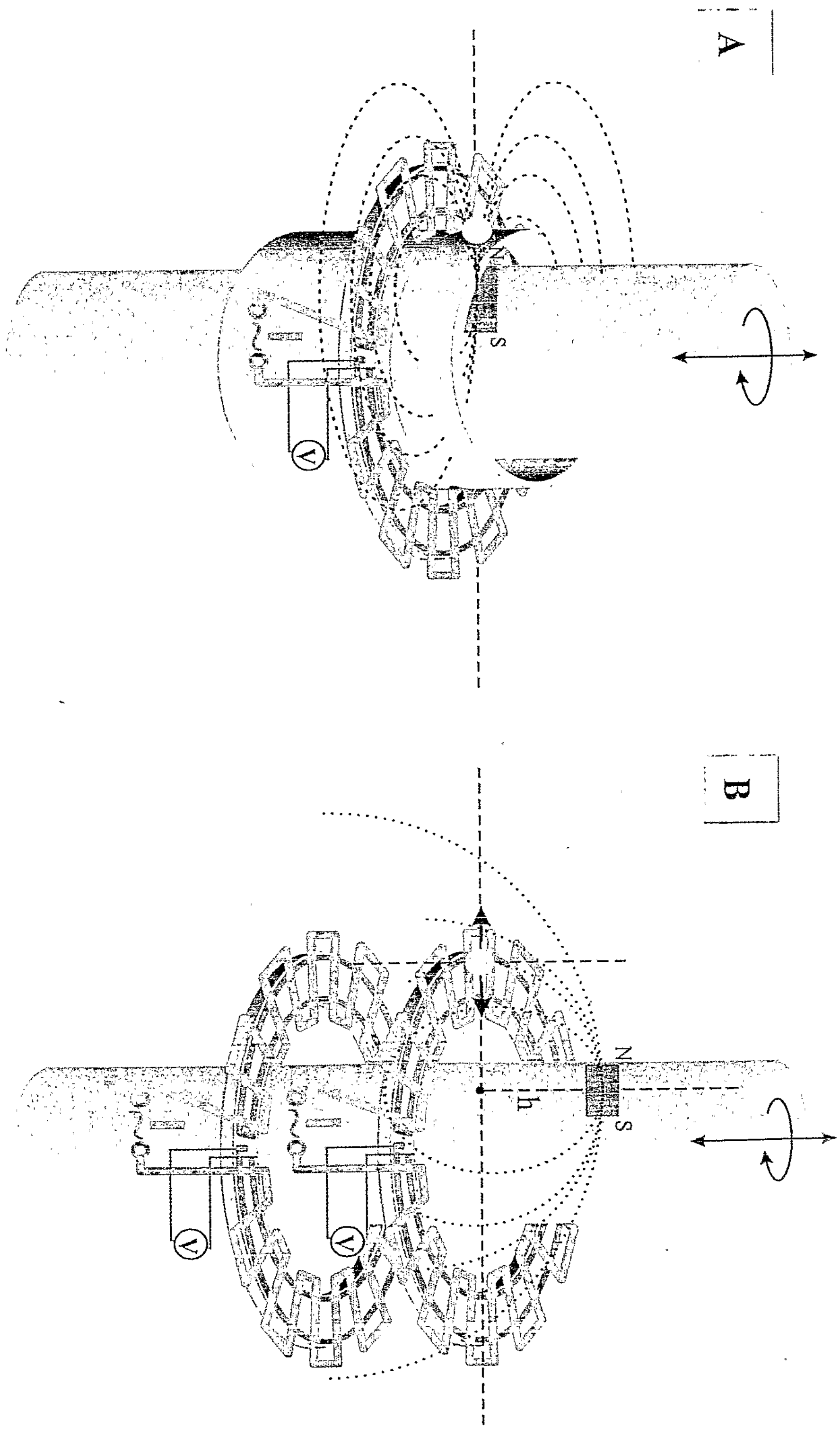
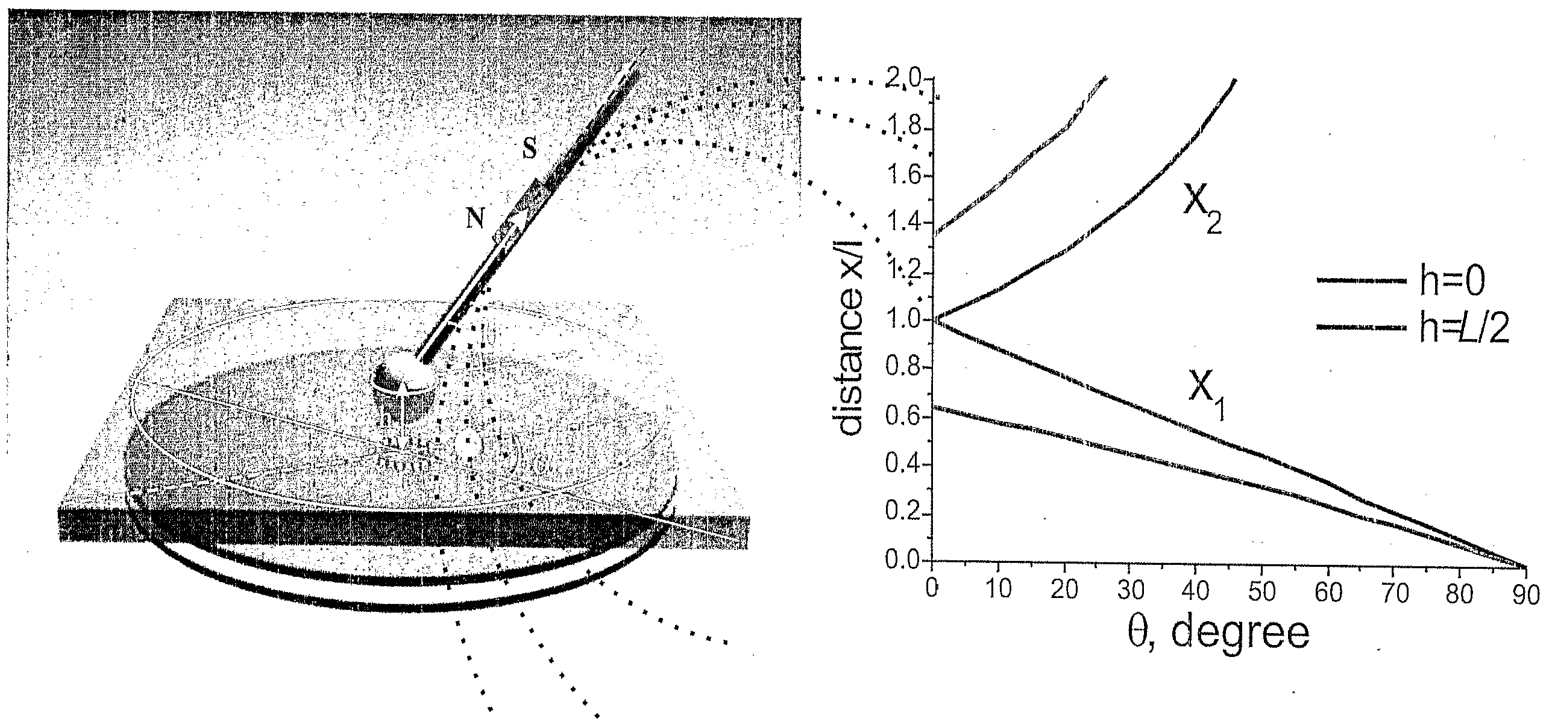


Fig 9

Fig 10



S
N
distance x/l
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
10
20
30
40
50
60
70
80
90
θ, degree
X_2
X_1
h=0
h=L/2